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Electromagnetic Compatibility in Air Insulation Substation

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In this work, transient coupling between the bus bars of the Air Insulation Substation (AIS) and the control cable located at its proximity is analyzed. The present study accounts for the real complex geometry of the bus bars and the finite conductivity of the soil. A time domain formulation of the problem is proposed in this work. The direct time domain formulation based on the use of Transmission Line (TL) theory and the Finite Difference Time Domain (FDTD) solution method. The excitations are given in the form of the localized current or voltage generator, respectively, and related electrical field radiated by bus bars. To ensure the electromagnetic compatibility (EMC) requirements the current induced in the transmission cable is analyzed by means of the Pencil Method that will allow one to identify the dominant frequencies in the interference signal. Various illustrative examples are given in the paper.

Key words: Electromagnetic coupling to transmission lines, FDTD method, Substations, Switching operation

Elektormagnetska kompatibilnost kod zrakom izoliranih transformatorskih stanica. U ovom radu analizira se tranzijentna sprega između sabirnica zrakom izoliranih transformatorskih stanica i kontrolnog kabela u njenoj blizini. Ovom analizom uzima se obzir složena geometrija sabirnica i konačna vodljivost tla. Direktna vremenska formulacija zasniva se na teoriji prijenosnih linija i metodi konačnih diferencija u vremenskom području. Pobude su dane u vidu lokaliziranih strujnih, donosno naponskih generator i odgovarajućeg električnog polja kojeg zrače sabirnice. Da bi se osigurali zahtjevi elektromagnetske kompatibilnosti struja inducirana u prijenosnoj liniji analizira se primjenom Pencil Method koja omogućava identifikaciju dominantnih frekvencija u interferencijskom signalu.Razni ilustrativni primjeri se obrađuju u radu.

Ključne riječi: elektromagnetska sprega s prijenosnim linijama, metoda konačnih diferencija u vremenskom području, transformatorske stanice, operacije prekakapčanja

1 INTRODUCTION

The fault, lightning and switching operations in UHV or HV substations cause very high altitude voltages and currents distributed along the busbars and the power lines. Among them, the wave phenomena caused by the switching operation due to the circuit breakers and the disconnect switchers is significant. As the frequency spectrum of the transient phenomena is rather wide and the high frequency electromagnetic fields are radiated from the busbars and the power lines, the switching transient constitutes a very challenging problem in the substation as it can seriously disturb the secondary equipment in the substation and the consumer devices nearby.

The electromagnetic radiation of air insulation UHV or HV substation, due to the switching operation, is particularly relevant to companies that transmit electrical energy. In this regard, the reader is referred to the work published in [1, 2], and very recently in [3]. The work in this paper is carried out by analyzing a problem of electromagnetic coupling to a shielded cable inside a substation.

The present work deals with a generalized model taking into account the finite conductivity of the cable shield and the ground as the return conductor thus providing one to take into account the variation of the per unit length parameters with frequency.

Therefore, the model analyzes the induced voltage on a control signal cable in substations while the switch operation is taking place featuring the use of FDTD method of solution for the assessment of voltage and current distributed along the busbar. The electric field radiated by the busbar is carried out using the Hertz dipole formulation [2] and the modified image theory to account for the finite conductivity to the soil [4].

Finally, the interaction between the EM wave emitted and the shielded cable is studied by using the Taylor approach [5] and the Matrix Pencil method [6] to characterize the parasite disruption by analyzing the poles position and residues and extracting the dominant poles.

2 TRANSIENT ANALYSIS OF WAVE PROCESSES FOR MULTI-CONDUCTOR TRANSMISSION LINES USING FDTD

In the case of the overhead line where the soil of finite conductivity is the return conductor, the TL equations in the time domain are, as follows [5]:

$$\frac{\partial}{\partial z}\left[u\left(z,t\right)\right]+\left[L\right].\frac{\partial}{\partial t}\left[i\left(z,t\right)\right]+\left[z'\left(t\right)\right]\otimes\left[i\left(z,t\right)\right]=\left[U_F\left(z,t\right)\right] \tag{1}$$

$$\frac{\partial}{\partial z}\left[i\left(z,t\right)\right]+\left[C\right].\frac{\partial}{\partial t}\left[u\left(z,t\right)\right]=\left[I_F\left(z,t\right)\right] \tag{2}$$

where $\otimes$ denotes the convolution product, matrices [L], [C] and [G] are the per-unit-length (PUL) inductance, capacitance and conductance matrices, respectively, while the multiconductor line (MTL) is assumed to be lossless and the soil is an infinite perfect conductor plane. Furthermore, $z'\left(t\right)$ is the Fourier transform of $\left[Z_g\right]$ which stands for the impedance due to the finite conductivity of soil.

It is not straightforward to derive the analytical time domain for $\left[Z_g\right]$. Thus, (1) is rewritten as follows [7]:

$$\begin{aligned}&\frac{\partial}{\partial z}\left[u\left(z,t\right)\right]+\left[L\right]\frac{\partial}{\partial t}\left[i\left(z,t\right)\right]\\&+\int_0^t\left[\zeta_g\left(t-\tau\right)\right]\frac{\partial}{\partial\tau}\left[i\left(z,\tau\right)\right]d\tau\\&+\int_0^t\left[\zeta_s\left(t-\tau\right)\right]\frac{\partial}{\partial\tau}\left[i\left(z,\tau\right)\right]d\tau=\left[U_F\left(z,t\right)\right]\end{aligned} \tag{3}$$

where $\left[\xi_g\right]$ is the transient ground resistance matrix whose elements are given in [8] and [9].

By using the FDTD method and by decomposing the line in current and voltage nodes [10], following equations are obtained:

$$\begin{aligned}&\left(\tfrac{[L]}{\Delta t}+\tfrac{3}{2}\left[\xi_g\left(\Delta t\right)\right]+\tfrac{1}{2}\left[\xi_s\left(\Delta t\right)\right]+\tfrac{[IMAT]}{2\Delta t}\right)\left[i_k^n\right]=\\&\left(\tfrac{[L]}{\Delta t}+\tfrac{3}{2}\left[\xi_g\left(\Delta t\right)\right]+\tfrac{1}{2}\left[\xi_s\left(\Delta t\right)\right]\right)\left[i_k^{n-1}\right]\\&+\left(\left[\xi_s\left(\Delta t\right)\right]+\tfrac{[IMAT]}{2\Delta t}\right)\left[i_k^{n-2}\right]-\tfrac{\left[u_{k+1}^n\right]-\left[u_k^n\right]}{\Delta z}\\&+\tfrac{1}{2}\textstyle\sum_{j=0}^{n-2}\left\{\left[\left[\xi_g\left(\left(n-1-j\right)\Delta t\right)\right]+\left[\xi_s\left(\left(n-1-j\right)\Delta t\right)\right]\right.\right.\\&\left.\left.+\left[\xi_g\left(\left(n-j\right)\Delta t\right)\right]+\left[\xi_s\left(\left(n-j\right)\Delta t\right)\right]\right]\times\left(\left[i_k^{j+1}\right]-\left[i_k^j\right]\right)\right\}\\&-\tfrac{\left[E_{T,k+1}^n\right]-\left[E_{T,k}^n\right]}{\Delta z}+\tfrac{\left[E_{L,k}^n\right]+\left[E_{L,k}^{n-1}\right]}{2}\end{aligned} \tag{4}$$

k=1,2,...,kmax-1

$$\left[\frac{[C]}{\Delta t}\right]\left[u_k^n\right]=\left\{\left[\frac{[C]}{\Delta t}\right]\left[u_k^{n-1}\right]-\frac{\left(\left[i_k^{n-1}\right]-\left[i_{k-1}^{n-1}\right]\right)}{\Delta z}-[C]\frac{\left[E_{T,k}^n\right]-\left[E_{T,k}^{n-1}\right]}{\Delta t}\right\} \tag{5}$$

k=2,...,kmax-1

where $\left[\xi_g\right]$ is the transient ground resistance matrix whose elements are given in [9] and [10]. $\left[\zeta_s\right]$ and $\left[IMAT\right]$ is outlined in the appendix.

2.1 Relationship between the current and the voltage at the both ends of the MTL in the time domain

In the frequency domain, the MTLs can be represented by multipole using matrix chain [Φ]. In this representation, the current-voltage at both ends of the line can be written as follows [5]:

$$\begin{aligned}&\begin{bmatrix}\left[\underline{\phi}_{11}\left(L\right)\right] & \left[\underline{\phi_{12}}\left(L\right)\right] & -\left[1_{Ni}\right] & [0]\\ \left[\underline{\phi_{21}}\left(L\right)\right] & \left[\underline{\phi}_{22}\left(L\right)\right] & [0] & -\left[1_{Ni}\right]\end{bmatrix}\\&.\begin{bmatrix}\left[\underline{U}\left(0\right)\right]\\ \left[\underline{I}\left(0\right)\right]\\ \left[\underline{U}\left(L\right)\right]\left[\underline{I}\left(L\right)\right]\end{bmatrix}=\\&\int_0^L-\left[\phi(L-\tau)\right]\begin{bmatrix}\left[\underline{U}_F(\tau)\right] & \left[\underline{I}_F(\tau)\right]\end{bmatrix}d\tau\end{aligned} \tag{6}$$

where 0 and *L* indicate the left and the right extremities, respectively.

In this work, the same notation is used in the time domain. Two fictitious current nodes are introduced and indicated by 0 (in z=0) and L (in z = L). These fictitious unknowns are due to $i_n(0)$, $i_n(L)$, $u_n(0)$ and $u_n(L)$. They are obtained by substituting Δz with Δz/2 in (5) for k=1 (z=0) and k=kmax+1 (z=L) and by introducing an average of the current calculated between two instants nΔt and (n-1) Δt.

Therefore, it follows:

for *k=1*

$$\begin{aligned}\tfrac{[C]}{\Delta t}\left[u^n\left(0\right)\right]-\tfrac{\left[i^n(0)\right]}{\Delta z}&=\tfrac{[C]}{\Delta t}\left[u^{n-1}\left(0\right)\right]-\tfrac{\left[i_1^{n-1}\right]}{(\Delta z/2)}+\tfrac{\left[i^{n-1}(0)\right]}{(\Delta z)}\\&-[C]\tfrac{\left[E_{T,1}^n\right]-\left[E_{T,1}^{n-1}\right]}{\Delta t}\end{aligned} \tag{7}$$

for *k=kmax+1*

$$\begin{aligned}&\frac{[C]}{\Delta t}\left[u^n\left(L\right)\right]+\frac{\left[i^n\left(L\right)\right]}{\Delta z}=\frac{[C]}{\Delta t}\left[u^{n-1}\left(L\right)\right]+\frac{\left[i_{k\max-1}^{n-1}\right]}{(\Delta z/2)}\\&-\frac{\left[i^{n-1}\left(L\right)\right]}{(\Delta z)}-[C]\frac{\left[E_{T,k\max+1}^n\right]-\left[E_{T,k\max+1}^{n-1}\right]}{\Delta t}\end{aligned} \tag{8}$$

Equations (7) and (8) are rewritten in the form of a single relation given by:

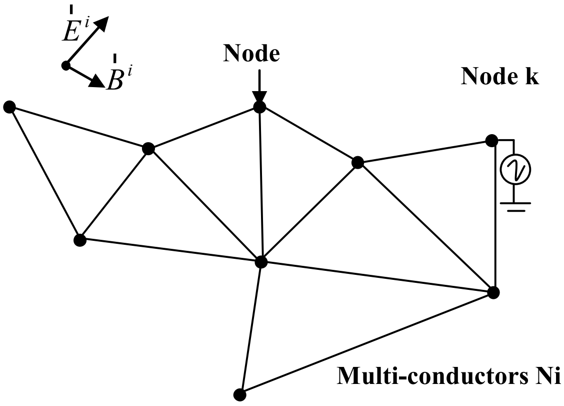


Fig. 1: Illustration of a network illuminated by electromagnetic wave and excited by localized generator

$$\begin{bmatrix} \frac{[C]}{\Delta t} & -\frac{1}{\Delta z}\left[1_{Ni}\right] & [0] & [0] \\ [0] & [0] & \frac{[C]}{\Delta t} & \frac{1}{\Delta z}\left[1_{Ni}\right] \end{bmatrix} \begin{bmatrix} u^n(0) \\ i^n(0) \\ u^n(L) \\ i^n(L) \end{bmatrix} =$$

$$\begin{bmatrix} \frac{[C]}{\Delta t}\left[u^{n-1}(0)\right] - \frac{\left[i_1^{n-1}\right]}{(\Delta z/2)} + \frac{\left[i^{n-1}(0)\right]}{(\Delta z)} \\ \frac{[C]}{\Delta t}\left[u^{n-1}(L)\right] + \frac{\left[i_{k\max-1}^{n-1}\right]}{(\Delta z/2)} - \frac{\left[i^{n-1}(L)\right]}{(\Delta z)} \\ -[C]\frac{\left[E_{T,1}^{n}\right]-\left[E_{T,1}^{n-1}\right]}{\Delta t} \\ -[C]\frac{\left[E_{T,k\max+1}^{n}\right]-\left[E_{T,k\max+1}^{n-1}\right]}{\Delta t} \end{bmatrix} \tag{9}$$

where $[1_{Ni}]$ is identity matrix of order Ni.

The presented method must address both the incident field illumination as well as the source voltage or current excitation.

3 MATRIX SYSTEM FOR A NETWORK

To model the problem of powering the busbar in AIS and then calculate the currents induced in a control cable illuminated by the transient electromagnetic wave, one has to solve a matrix system which successively treats:

- a transient wave propagation in a meshed or radial network following the closing of a switch;
- electromagnetic coupling between a transient wave and a radial or meshed network.

Consider a network which contains NL uniform MTL's interconnected by M localized networks (nodes). Each MTL contains Ni (i=1…NL) conductors.

Figure 1 shows a transmission line system excited by an external electromagnetic field and a localized generator.

The first step defines a matrix [A] composed of two sub-matrixes:

$$[A] = \begin{bmatrix} [A_1] \\ [A_2] \end{bmatrix} \tag{10}$$

[A1] is the sub-matrix derived from terminal conditions for all tubes (lines) described in sub-section A.

[A2] is the sub-matrix derived from Kirchhoff's laws (KCL and KVL) for junctions (termination's and interconnection's networks) [8].

Once matrix [A] is determined, the solution of equation (11) yields unknown electrical variables.

$$[A] \cdot [X] = [B], \tag{11}$$

where [X] is the unknown vector (current and voltage nodes) and [B] stands for the source vector. The details of the system derivation are given in the Appendix 1.

4 AN OUTLINE OF THE PENCIL METHOD

The matrix pencil method models the time-domain sequence as a sum of complex exponentials:

$$y(kT_s) = \sum_{i=1}^{M} R_i z_i^k + b(k), k = 0...., N-1, \tag{12}$$

Where

$$R_i = G_i e^{j\varphi_i} \; et \; z_i = e^{p_i \Delta t} = e^{\sigma_i + j2\pi f_i},$$
$$G_i \in \Re, \varphi_i \in \Re, (R_i, z_i) \in C^2$$

f_i, σ_i, G_i, φ_i are the frequencies, damping, magnitudes, and initial phases of the *i-th* modal component, respectively, while T_s is the sampling interval.

In (11), the residuals R_i and the complex exponentials z_i are unknowns to be determined by the *N* known values of the solution signal *y*. The number of exponentials used in the model, *M*, is a parameter which has a direct influence on the accuracy of the constructed model. The method uses a mathematical tool entitled matrix pencil,

$$[Y_2] - \lambda [Y_1], \tag{13}$$

where λ is a scalar parameter. Note that $[Y_1]$ and $[Y_2]$ are chosen as:

$$[Y_1] = \begin{bmatrix} y(0) & y(1) & \cdots & y(L-1) \\ y(1) & y(2) & \cdots & y(L) \\ \vdots & \vdots & \ddots & \vdots \\ y(N-L-1) & y(N-L) & \cdots & y(N-2) \end{bmatrix}_{(N-L)\times(L)} \tag{14}$$

$$[Y_2] = \begin{bmatrix} y(1) & y(2) & \cdots & y(L) \\ y(2) & y(3) & \cdots & y(L+1) \\ \vdots & \vdots & \ddots & \vdots \\ y(N-L-1) & y(N-L) & \cdots & y(N-1) \end{bmatrix}_{(N-L)\times(L)} \quad (15)$$

The generalized eigenvalues of the matrix pencil (13) are equal to the unknown complex exponentials of (12) [6]. Once parameter M is chosen and the complex exponentials are determined, one can readily find the residuals from the following system:

$$\begin{bmatrix} y(0) \\ y(1) \\ \vdots \\ y(N-1) \end{bmatrix} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ z_1 & z_2 & \cdots & z_M \\ \vdots & \vdots & \ddots & \vdots \\ z_1^{N-1} & z_2^{N-1} & \cdots & z_M^{N-1} \end{bmatrix} \cdot \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_M \end{bmatrix} \quad (16)$$

The details of the matrix pencil theory and the related algorithm can be found in [6].

5 SIMULATION RESULTS

The presented method is tested on the configuration shown in Fig 2. The busbar is 163 m long, 15.5 m high with a radius of 5.8 cm. The connection lines are respectively 86 and 40 meter long along x direction, 8.51 m high with a radius of 6.5 cm. A 300 m single-core shielded cable (Model: RG58A/U) under the busbar is buried on the soil. The inner radius and outer radius of the cable shield are 1.48 mm and 1.6 mm, respectively. The ground resistivity is 100Ω.m. The busbar is excited by the cosine voltage source. This application is related to the power busbars after the circuit breaker closes. With this closure the transient which responsible for a significant electromagnetic radiation is analyzed.

First, the case of unshielded cable (see Fig 2) is considered. Figure 3 shows the transient response of the induced current at the location B, obtained using the proposed method and the frequency domain NEC04 code [11] combined with the Inverse Fourier Transform.

The results obtained via different techniques agree relatively satisfactorily. Having validated the proposed method with NEC04 [11], one uses the parametric transformation by the method of pencils. This transformation provides us to reconstruct the response of the cable (the induced current) with a minimum number of frequencies and also allows us to define the modal energies. The aim is to extract the poles and residues of signal using the Matrix Pencil method [6]. The method derives the complex poles and residues from the time domain data. The transient response of the shielded cable is just a summation of all the residues multiplied by exponentially damped sinusoids. Furthermore, one considers the previous example where the circuit breaker closes in the substation with three different situations for the buried control cable. In the first case, there is a control cable unshielded, while in the second scenario, the cable is shielded and finally the third case corresponds to a guard conductor connected to the shield as shown in Fig 6. Figs 4, 5 and 7 show the current induced on the C location of the buried cable control (Fig 2) for the unshielded case, shielded only and shielded with a guard conductor, respectively.

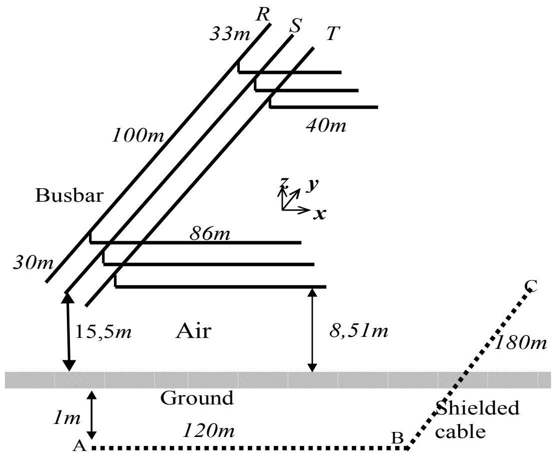


Fig. 2: Simplified geometry of a 500kV air insulation substation

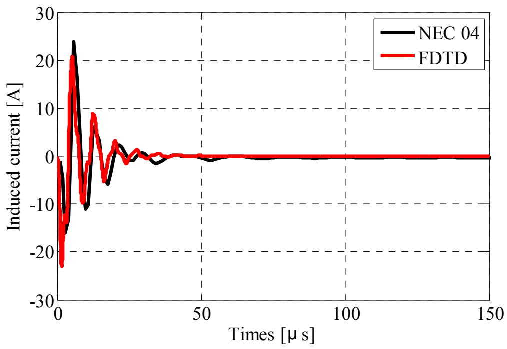


Fig. 3: Induced current at B extremity

In all three cases, the original signal obtained by simulation and the same signal reproduced by the method of pencils with a minimum number of frequencies is presented. Comparing the calculated results (Figs 4, 5 and 7) a difference in magnitude, which was expected due to the role of the shield and guard conductor, can be noticed.

Analyzing the results obtained by the method of Matrix Pencil show a clear difference in the spectral content of the induced current as depicted in Figs 8a, 8b and 8c.

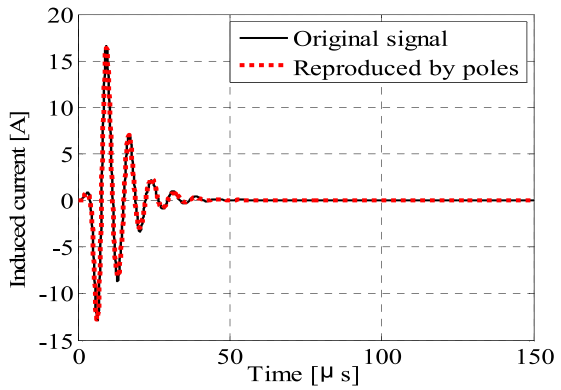


Fig. 4: Transient response for unshielded cable (7 poles)

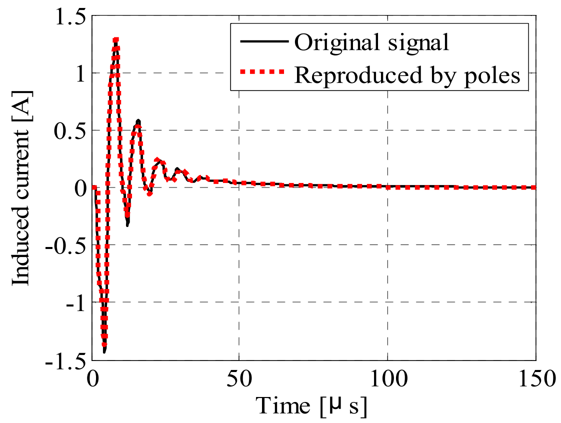


Fig. 5: Transient response for shielded cable (7 poles)

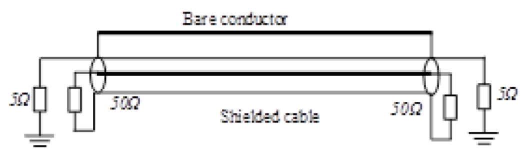


Fig. 6: Geometry considered

It has been found that all dominant frequencies in the signal response of the unshielded and shielded cable without guard conductor do not appear on the signal response with the guard conductor. Note that any values equal or close to the one for the residue are absent in the case of the shielded cable with the guard conductor (Fig 8b). For higher frequencies (near 0.4 MHz), it has been noticed that the residue is practically zero for the case of shielded cable only and for the shielded cable with a guard conductor. Figure 8a shows that the damping factor is smaller at around 0.4 MHz for the shielded cable and for shielded cable with a guard conductor, but at these frequencies the residue is close to zero. These results are in agreement with the modal distribution of energy in Fig 8c where high frequencies carry a very low energy in the case of shielded cable and in the presence of a guard conductor.

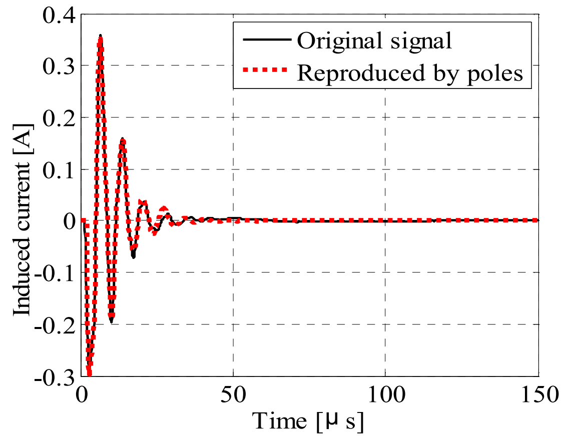


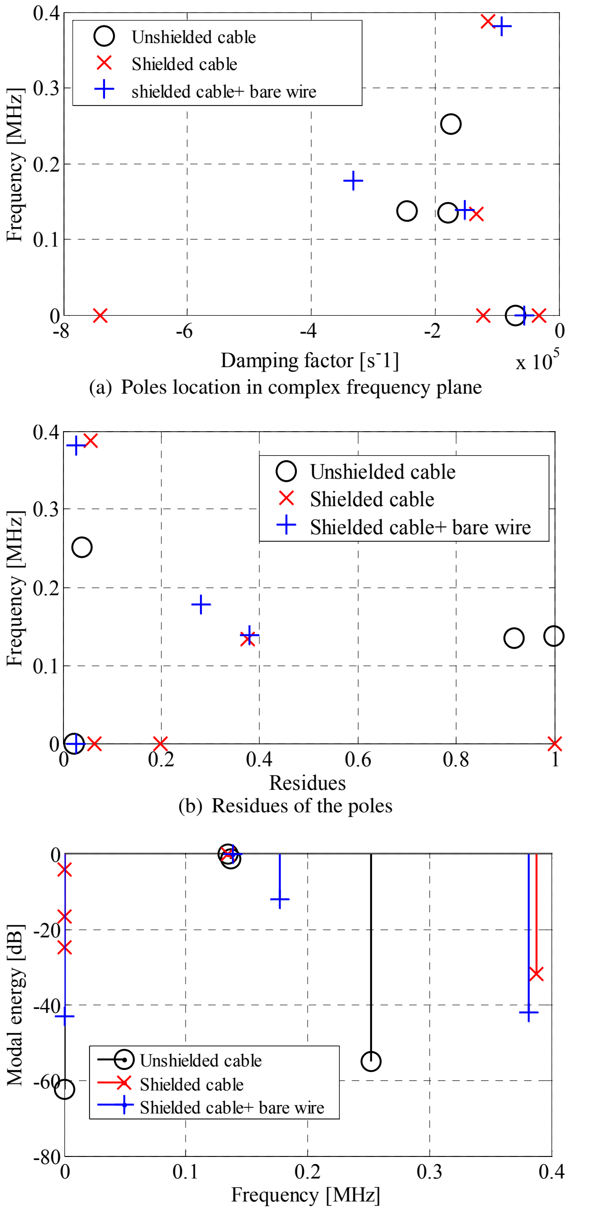
Fig. 7: Transient response for shielded cable + bare wire (7 poles)

The signal analysis by the method of Pencils, shows that the energy (Fig 8c) is mainly driven by the frequencies 0.1343MHz and 0.137MHz in the case of unshielded cable, by the frequency 0.1341 MHz for the shielded cable and by the frequency f=0.138MHz for the shielded cable with a guard conductor. These results are confirmed in Figs 8a and 8b where we record the residues close to 1 with low damping factors for unshielded cable, and around 0.4 with low damping factors for shielded cable and for shielded cable with a guard conductor. The results also confirm that the energy of the DC component is very low. The possibility to analyze the electromagnetic compatibility issues by using the parametric analysis of the signal has been demonstrated, as well. Furthermore, it is also possible to reduce the spectral content to improve the electromagnetic compatibility (EMC) of the device.

6 CONCLUSION

In this paper, a time domain model for the near field coupling to transmission line is proposed to predict the electromagnetic interference to control cable due to the switching operation in a substation (Air Insulation Substation).

The signal analysis undertaken by Pencils defines the disturbing frequencies with significant energy. This im-



(a) Poles location in complex frequency plane

(b) Residues of the poles

(c) Modal energy

Fig. 8: An example of two figures spanning across two columns

portant information contained in the signal is used to implement protective measures and improve the EMC of the device. It is clear that the extraction of dominant frequencies in the interference signal can better address the EMC problem arising in and near the substations of power network, respectively. In addition to control cable near AIS the presented approach can be extended to other applications.

APPENDIX A

A.1 Construction of the unknown vector $[X]$

First, the vector of unknowns $[X]$ has to be defined. Vector $[X]$ includes the unknown currents and voltages at all nodes in the network. In the vector $[X]$ each line multiconductors of index i is represented by voltages and currents at both ends. At time $t = n.\Delta t$, the first end is indicated by 0 $u_i^n(0)$ and $i_i^n(0)$ and the second by L $u_i^n(L)$ and $i_i^n(L)$.

By taking into account these considerations, for the line index i, at $t = n.\Delta t$ it follows:

$$[X] = \left[\begin{array}{l} \cdots \quad [u_i(0)^n] \quad [i_i(0)^n] \quad [i_i(0)^n] \\ [u_i(L)^n] \quad [i_i(L)^n] \quad \cdots \end{array} \right]^T \tag{17}$$

A.2 Construction of the sub matrices $[A_1]$ and $[A_2]$

In view of the representation of vector $[X]$ and by taking into account the relationship (9) the contribution of the multi-conductors line with index i appear in the sub matrix $[A_1]$:

$$[A_1] = \begin{bmatrix} \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \cdots & \left(\frac{[C]}{\Delta t}\right) & -\frac{1}{\Delta z}[1_{Ni}] & 0 & 0 & \cdots \\ & [0] & [0] & \left(\frac{[C]}{\Delta t}\right) & \frac{1}{\Delta z}[1_{Ni}] & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix} \tag{18}$$

The sub matrix $[A_2]$ is obtained using the laws of Kirchhoff in voltage and current (KCL and KVL) at each node m of the tube [5]:

$$\sum_{k=1}^{N} \left([Y_k^m]\,[v_k^m] + [Z_k^m]\,[i_k^m] \right) = [P^m] \tag{19}$$

where $[Z_k^m]$ and $[Y_k^m]$ are matrices resulting from the application of the Kirchhoff's laws (KVL and KCL) at node m, and impedances or admittances of the network node index m. $[P^m]$ is the vector of current or voltage localized sources.

A.3 Construction of the subvectors $[B_1]$ and $[B_2]$

The subvector $[B_1]$ is constructed from the second member of the system (9). For the conductor of index i

at $t = n.\Delta t$ one has:

$$\begin{bmatrix} \vdots \\ \frac{[C]}{\Delta t}\ \left[u^{n-1}(0)\right] - \frac{\left[i_1^{n-1}\right]}{(\Delta z/2)} + \frac{\left[i^{n-1}(0)\right]}{(\Delta z)} \\ \frac{[C]}{\Delta t}\ \left[u^{n-1}(L)\right] + \frac{\left[i_{k\max-1}^{-1n}\right]}{(\Delta z/2)} - \frac{\left[i^{n-1}(L)\right]}{(\Delta z)} \\ \vdots \\ \vdots \\ -[C]\,\frac{\left[E_{T,1}^{n}\right]-\left[E_{T,1}^{n-1}\right]}{\Delta t} \\ -[C]\,\frac{\left[E_{T,k\max+1}^{n}\right]-\left[E_{T,k\max+1}^{n-1}\right]}{\Delta t} \\ \vdots \end{bmatrix} \tag{20}$$

The currents $\left[i_1^{n-1}\right]$ and $\left[i_{k_{\max}-1}^{n-1}\right]$ are calculated from the recurrence equations (4).

For a transmission line system excited by the external electromagnetic field, the subvector $[B_2]$ is zero but in the case of localized generator a local generator $[P_m]$ expressed by the an analytical expression in second member of the relation (A.3) is introduced.

APPENDIX B

$$[\zeta_s] = F^{-1}\left\{\frac{[Z_s]}{j\omega}\right\} = F^{-1}\left\{\frac{1}{j\omega}\begin{bmatrix} [Z_{s1}] & [0] & \cdots & [0] \\ [0] & [Z_{s2}] & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ [0] & \cdots & \cdots & [Z_{sn}] \end{bmatrix}\right\} \tag{21}$$

$$[\zeta_s] = \begin{bmatrix} [\zeta_{s1}] & [0] & \cdots & [0] \\ [0] & [\zeta_{s2}] & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ [0] & \cdots & \cdots & [\zeta_{sn}] \end{bmatrix} \tag{22}$$

The elements of the resistance submatrix of the shield are given as follows:

$$[\zeta_{sj}] = \begin{bmatrix} 2\zeta_0(t) - 2\zeta_m(t) & \zeta_0(t) - \zeta_m(t) \\ \zeta_0(t) - \zeta_m(t) & \zeta_0(t) \end{bmatrix} \tag{23}$$

With [12]:

$$\zeta_0(t) \cong K_\delta \delta(t) + R_{dc} + \sum_{k=1}^{N0} \zeta_{ok}(t)$$

$$K_\delta = \frac{2\mu_s d}{\pi^2}\sum_{k=N_0+1}^{\infty}\frac{1}{k^2} = \frac{2\mu_s d}{\pi^2}\left(\frac{\pi^2}{6} - \sum_{k=1}^{N_0}\frac{1}{k^2}\right)$$

$$R_{dc} = \frac{1}{2\pi a}\frac{1}{\sigma_s d}$$

$$\zeta_{0k}(t) = 2R_{dc}e^{-k^2\pi^2 t/\tau_s}$$

$$\zeta_{mk}(t) = 2R_{dc}(-1)^k e^{-k^2\pi^2 t/\tau_s}$$

$$\tau_s = d^2\mu_s\sigma_s$$

$$\zeta_m(t) \cong \begin{cases} 0 & for\ t = 0 \\ R_{dc} + \sum_{k=1}^{Nm}\zeta_{mk}(t) & for\, t > 0 \end{cases}$$

$$[IMAT] = \begin{bmatrix} [IMAT_1] & [0] & \cdots & [0] \\ [0] & [IMAT_2] & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ [0] & \cdots & \cdots & [IMAT_n] \end{bmatrix}$$

$$\begin{aligned} IMAT_j = & \\ & \begin{bmatrix} 2\int_0^{\Delta t}\zeta_0(t)\,dt - 2\int_0^{\Delta t}\zeta_m(t)\,dt \\ \int_0^{\Delta t}\zeta_0(t)\,dt - \int_0^{\Delta t}\zeta_m(t)\,dt \end{bmatrix. \\ & \left.\begin{matrix} \int_0^{\Delta t}\zeta_0(t)\,dt - \int_0^{\Delta t}\zeta_m(t)\,dt \\ \int_0^{\Delta t}\zeta_0 \end{matrix}\right] \\ & = \begin{bmatrix} 2In_0 - 2In_m & In_0 - In_m \\ In_o - In_m & In_0 \end{bmatrix} \end{aligned}$$

$$\begin{aligned} In_0 =& K_\delta \\ &+ R_{dc}\Delta t + \sum_{k=1}^{N_0} 2R_{dc}\left(-\frac{\tau_s}{k^2\pi^2}\right)\ \left[e^{-k^2\pi^2\frac{\Delta t}{\tau_s}} - 1\right] \\ In_m =& R_{dc}\Delta t \\ &+ \sum_{k=1}^{N_m} 2R_{dc}(-1)^k\left(-\frac{\tau_s}{k^2\pi^2}\right)\ \left[e^{-k^2\pi^2\frac{\Delta t}{\tau_s}} - 1\right] \end{aligned}$$

REFERENCES

[1] C.M. Wiggins, S.E. Wright, "Switching transient field in substations," IEEE Transactions on Power Delivery, vol. 6, No. 2, , pp. 591–600. April 1991.

[2] B. Nekhoul, R. Feuillet, and J. C. Sabonnadiere, "Prediction of transient electromagnetic environment in power networks," IEEE Transactions on Magnetics, vol. 30, No. 5, pp. 3745–3748, September. 1994.

[3] L. QI, X. CUI, "Near field coupling to shielded cable due to switching operation in substation," Frontiers of Electrical and Electronic Engineering in China, vol. 3, No. 3, pp. 347–352, 2008.

[4] T. Takashima, T. Nakae and R. Ishibashi "High frequency characteristics of impedances to ground and field distribution of ground electrodes," IEEE Transactions on power apparatus and systems, vol. PAS-100, No.4, April 1981.

[5] C.R.Paul, " Analysis of multiconductor Transmission lines," John Wiley & Sons, Inc.,New York, 1994.

[6] Y. Hua, T.K. Sarkar, "Generalised pencil-of-function method for extracting poles of an EM system from its transient response," IEEE Transactions on Antennas and Propagation, vol. 37, No. 2, pp. 229-234, February 1989.

[7] A. Ametani, " A General Formulation of Impedance and Admittance of cables," IEEE Trans on Power Apparatus and systems, vol.PAS-99, No.3, May/June 1980.

[8] S. Kaouche, B. Nekhoul, K. Kerroum, K. El Khamlichi drissi, F. Paladian, " Induced lightning disturbances in a network of aerial shielded cables," Annals of telecommunications, vol. 62, No.7-8, pp. 894-924, 2007.

[9] S.L. Loyka, "On the calculation of the ground transient resistance of overhead lines," IEEE Transactions on Electromagnetic Compatibility, vol.41, No.3, pp.193-195, February1999.

[10] F. Rachidi, S.L. Loyka, CA. Nucci and M. Ianoz, "A new expression for ground transient resistance matrix elements of Multiconductor overhead transmission lines," Journal of Electric Power System Research, vol. 65, No. 1, pp.41-46, 2003.

[11] Gerald J.Burke, Numerical Electromagnetic Code-NEC-4. January, 1992.

[12] M. Feliziani and F. Maradi, "Field analysis of penetrable conductive shields by the finite-difference time-domain method with impedance network boundary conditions (INBCs)," IEEE Transactions on Electromagnetic Compatibility, vol.41, No.4, pp. 307-319, November 1999.

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